(b) Pools

by

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The burning of liquid droplets and spheres considered in the previous section is instructive, since these are cases for which theoretical solutions may be directly obtained. The next more complex, yet still 'simple' case is of the liquid (or thermoplastic) pool. Over the last 3 or so decades, an enormous number of studies have been conducted where pool burning was considered theoretically or measured empirically. The most systematic early study was by two Russian researchers, Blinov and Khudiakov [1]. Their results were analyzed by Hottel [2], who pointed out that conservation of energy can be applied to the pool:

$$\dot{q} = \dot{q}'' \times A = \left(\dot{q}_r'' + \dot{q}_c'' - \dot{q}_{rr}'' - \dot{q}_{misc}''\right) \times \left(\frac{\Delta h_c}{\Delta h_g}\right) \times A \qquad (1)$$

where $\dot{q}$ is the heat release rate of the pool; double-prime denotes per unit area; A is the area of the pool; $\dot{q}''_r$ is the radiant heat flux absorbed by the pool; $\dot{q}''_c$ is the convective heat flux to the pool; $\dot{q}''_{rr}$ is the heat flux re-radiated from the surface of the pool; and into $\dot{q}''_{misc}$ are lumped wall conduction losses and non-steady terms. The heat of gasification is Δh_g, while the (lower) heat of combustion is Δh_c. Since most of the older data that we shall discuss were gathered by simple load cell measurements, rather than by current-day heat release rate measurements, it appropriate to remember that

$$\dot{q} = \dot{m}'' \times \Delta h_c \times A \qquad (2)$$

Hottel's analysis of Blinov and Khudiakov's data showed two basic regimes are possible: radiatively dominated burning for large pool diameters,D, and convectively dominated burning for small D. Furthermore, in the convective regime the flow can be either laminar or turbulent (being always turbulent for radiatively driven pools), while in the radiative regime the flames can be optically thin or thick. These distinctions can, in the simplest analysis, be made solely on the basis of pool diameter. Such a simple classification is possible if the pool is strictly circular, radiant heating is only from the pool's flames and not augmented by external sources, and there are no interferences to the flow streamlines which could 'trip' the onset of turbulence. In such a simplified case:

D (m)	Burning Mode
<0.05	convective, laminar
0.05–0.2	convective, turbulent
0.2–1.0	radiative, optically thin
>1.0	radiative, optically thick

In practice, where room fires or fire test equipment is concerned, external heating may be present, pools may be non-circular, and disturbances may be present. In such cases, the onset of turbulence will occur at smaller diameters than stated. The above classification is useful, nonetheless, for it permits data from specially set up pool fire experiments to be analyzed in a way which can give meaningful guidance for various other applications.

In the convective limit (small pools), based on Eq. 1 we would expect that

$$\dot{q} = \dot{q}_c'' \times \left(\frac{\Delta h_c}{\Delta h_g}\right) \times A \qquad (3)$$

Behavior in the convective laminar mode has not been fully correlated, although Blinov and Khudiakov and Corlett and Fu [3] indicate expected functional relations of the form

$$\dot{q}'' \text{ or } \dot{m}'' \propto aD^{-n} + b \qquad (4)$$

with $1/2 < n \leq 3/2$. For the convective turbulent mode, the $\dot{q}''$ values are independent of D and at their lowest. DeRis and Orloff have provided a dimensionless correlation [4] based on fuel thermochemical properties.

In the radiative mode, both the optically thick and thin regimes might be modeled if we let

$$\dot{m}'' = \sigma T_f^4 (1 - e^{-k\beta D}) \qquad (5)$$

where σ is the Stefan-Boltzmann constant, and T_f is an effective grey-gas flame temperature. It should be related to the measured temperatures in the hottest zone, but a predictive relationship is not available [5]. The effective flame volume emissivity is represented by $(1 - e^{-k\beta D})$, where k is the absorption-extinction

coefficient of the flame, D is the pool diameter, and β is a 'mean-beam-length corrector.'

For most fuels, reliable measurements exist only for $\dot{m}''$ as a function of D, and not for T_f, k, or β separately. Zabetakis and Burgess first recommended that the existing experimental data can be well represented by the form

$$\dot{m}'' = \dot{m}''_\infty (1 - e^{-k\beta D}) \qquad (6)$$

This requires determining two empirical factors: $\dot{m}''_\infty$ and $(k\beta)$, not separated into k and β. Contrary to initial expectation, analysis of experimental data [5] indicates that the value of β is not a universal geometrical factor, but varies widely with the type of fuel considered. This is the reason why separating out the k and the β would not facilitate data interpretation.

COMPILATION OF DATA

The experimental data available from a large number of investigations into pool burning were analyzed numerically in the form given by Eq. 5. From the available data points, values of $k\beta$ and $\dot{m}''_\infty$ were determined using a numerical algorithm for nonlinear curve fitting. Eq. 5 proved to be inappropriate for one category of fuels: alcohols. For alcohols, a functional form of

$$\dot{m}'' = \dot{m}''_\infty , \qquad D \geq 0.2 \ m \qquad (7)$$

was found to be suitable, instead. The results are given in Table 1. For illustration, the experimental data points and the curve fit are shown for three fuels in Figs. 1,2, and 3. Fig. 1 shows the results for gasoline, a typical fuel. Fig.

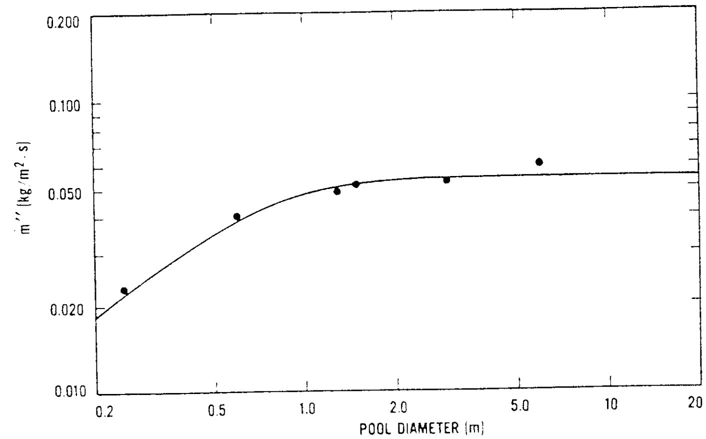

Figure 1. Pool burning rates for gasoline.

Table 1
Data for Large Pool Burning Rate Estimates

Material	Density (kg/m^3)	Δh_g (kJ/kg)	Δh_c (MJ/kg)	$\dot{m}''_\infty$ ($kg/m^2 \cdot s$)	$k\beta$ (m^{-1})	k (m^{-1})	T_f (K)
Cryogenics							
Liquid H_2	70	442	120.0	0.017 (±0.001)	6.1 (±0.4)	—	1600
LNG (mostly CH_4)	415	619	50.0	0.078 (±0.018)	1.1 (±0.8)	0.5	1500
LPG (mostly C_3H_8)	585	426	46.0	0.099 (±0.009)	1.4 (±0.5)	0.4	—
Alcohols							
Methanol (CH_3OH)	796	1195	20.0	0.017 (±0.001)	a	—	1500
Ethanol (C_2H_5OH)	794	891	26.8	0.015 (±0.001)	a	0.4	1490
Simple Organic Fuels							
Butane (C_4H_{10})	573	362	45.7	0.078 (±0.003)	2.7 (±0.3)	—	—
Benzene (C_6H_6)	874	484	40.1	0.085 (±0.002)	2.7 (±0.3)	4.0	1460
Hexane (C_6H_{14})	650	433	44.7	0.074 (±0.005)	1.9 (±0.4)	—	1300
Heptane (C_7H_{16})	675	448	44.6	0.101 (±0.009)	1.1 (±0.3)	—	—
Xylenes (C_8H_{10})	870	543	40.8	0.090 (±0.007)	1.4 (±0.3)	—	—
Acetone (C_3H_6O)	791	668	25.8	0.041 (±0.003)	1.9 (±0.3)	0.8	—
Dioxane ($C_4H_8O_2$)	1035	552	26.2	0.018[b]	5.4[b]	—	—
Diethyl Ether ($C_4H_{10}O$)	714	382	34.2	0.085 (±0.018)	0.7 (±0.3)	—	—
Petroleum Products							
Benzine	740	—	44.7	0.048 (±0.002)	3.6 (±0.4)	—	—
Gasoline	740	330	43.7	0.055 (±0.002)	2.1 (±0.3)	2.0	1450
Kerosene	820	670	43.2	0.039 (±0.003)	3.5 (±0.8)	2.6	1480
JP-4	760	—	43.5	0.051 (±0.002)	3.6 (±0.1)	—	1250
JP-5	810	700	43.0	0.054 (±0.002)	1.6 (±0.3)	0.5	1250
Transformer oil, hydrocarbon	760	—	46.4	0.039[b]	0.7[b]	—	1500
Fuel oil, heavy	940–1000	—	39.7	0.035 (±0.003)	1.7 (±0.6)	—	—
Crude oil	830–880	—	42.5–42.7	0.022–0.045	2.8 (±0.4)	—	—
Solids							
Polymethylmethacrylate $(C_5H_8O_2)_n$	1184	1611	24.9	0.020 (±0.002)	3.3 (±0.8)	1.3	1260
Polyoxymethylene $(CH_2O)_n$	1425	2430	15.7			—	1200
Polypropylene $(C_3H_6)_n$	905	2030	43.2			1.8	1200
Polystyrene $(C_8H_8)_n$	1050	1720	39.7			5.3	1200

(a)—Value independent of diameter in turbulent regime.
(b)—Only two data points available.

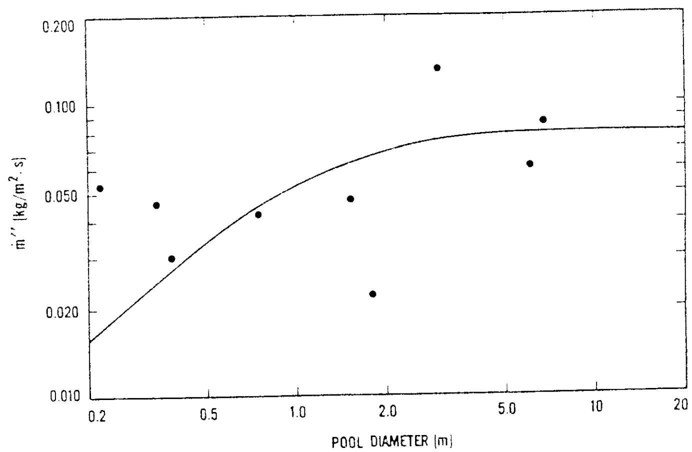

Figure 2. Pool burning rates for LNG, shown as an example of a fuel where experimental data show large variations.

2 gives results for liquified natural gas (LNG), chosen to illustrate the larger degree of scatter associated with cryogenic fuel measurements. Finally, Fig. 3 illustrates the behavior of alcohol fuels.

Use of tabulated data

The data in the table can be used directly to estimate the heat release rates of pools with D > 0.2 m, provided certain conditions are met. These are: that the pool be heated only by its own flame, that only the steady-state burning is of

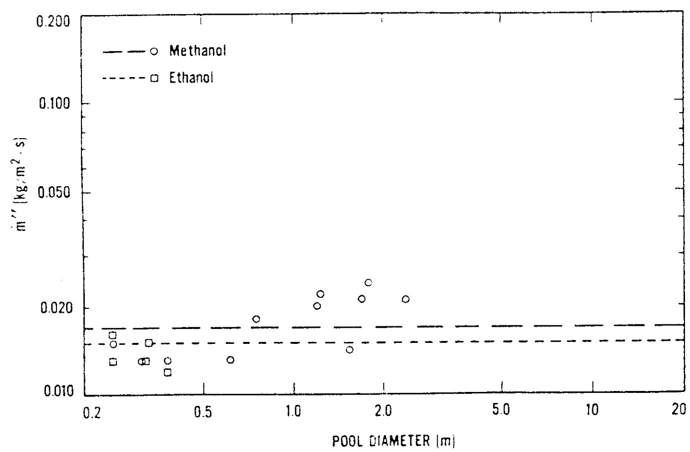

Figure 3. Pool burning rates for alcohols.

interest, that the environment is wind-free, and that it is not burning inside a tank where the fuel height is significantly below the top of the tank. In general, quantitative predictions for what happens when these constraints are not met are not available. For qualitative guidance, the reader can consult [5], where an additional discussion is presented for many of these effects.

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